National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Nulling at the Keck Interferometer

Mark Colavita, Section 383, and the KI development and operations teams at JPL, MSC/Caltech, and Keck Observatory

Exoplanet Science and Technology Fair
Von Karman Auditorium, JPL, 22 Feb 2008

W. M. KECK OBSERVATORY
On the summit of Mauna Kea, Island of Hawai'i

KI Overview

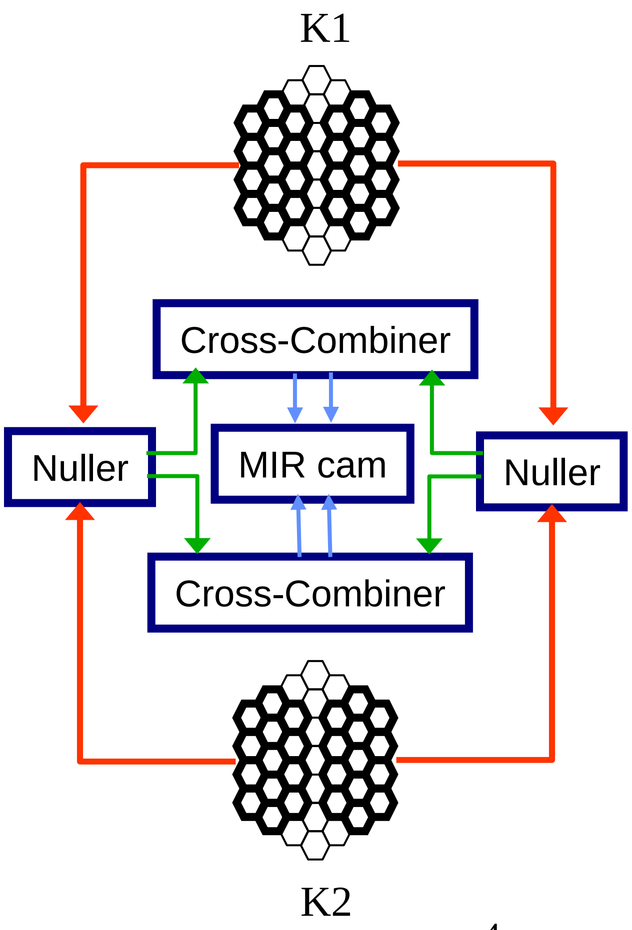
- Combines the two Keck telescopes as an Interferometer
  - Adaptive Optics (AO) on both telescopes
  - 2.2 um active fringe tracking
  - Lots of other active systems
- H & K band fringe visibility mode
  - High sensitivity measurements of planet-forming regions
  - Observations of a range of astrophysical objects
- 10 um nulling mode
  - Measure exozodiacal dust around nearby main sequence stars
    - » Improve on current SED measurements
    - » Support science planning for future exoplanet missions

Observing Modes

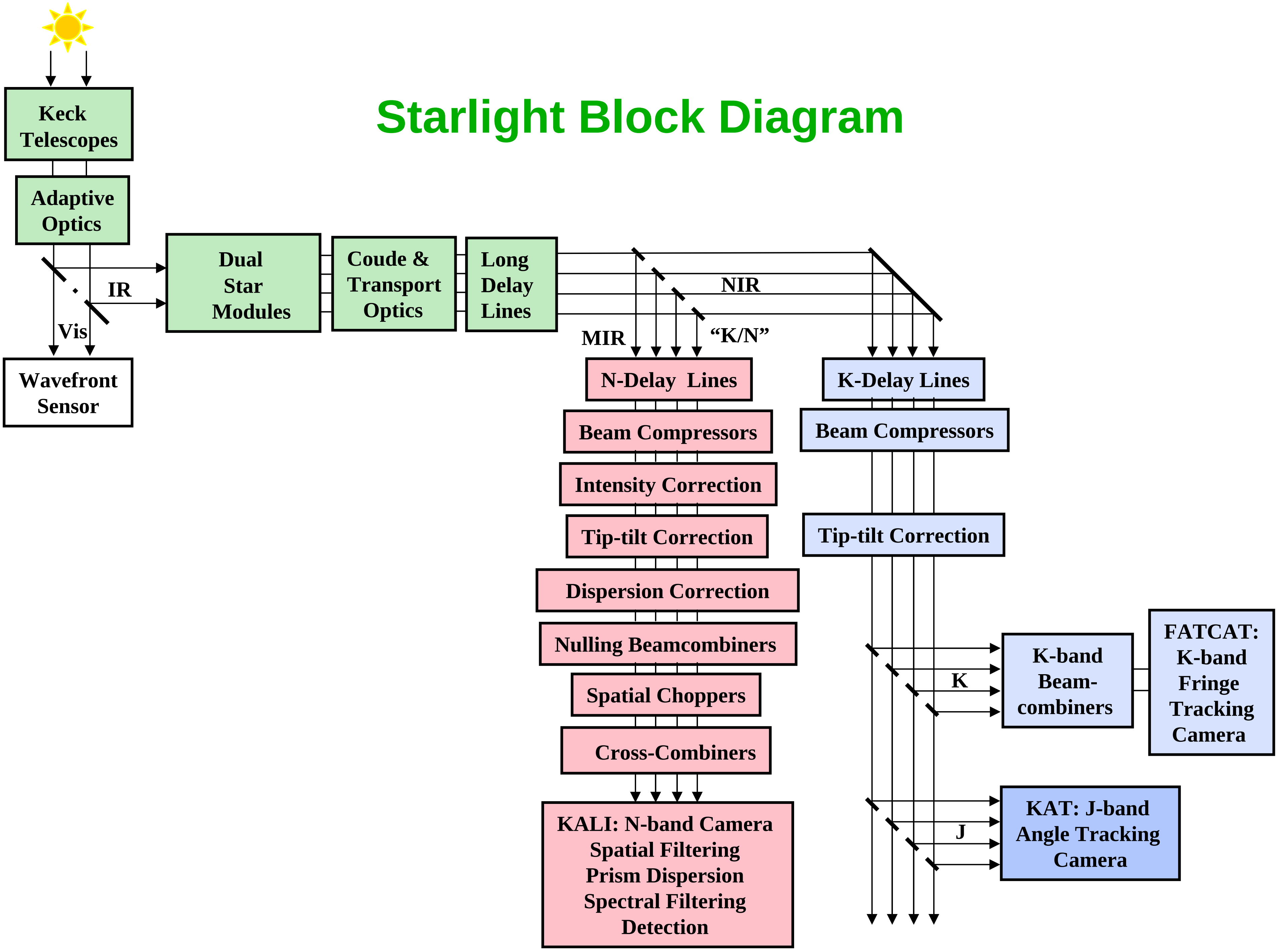
- V2 mode has been routinely available to the community since 2004
- Nuller has recently completed its development & validation, including shared-risk-science observations
- Nuller begins its Key Science program this month. Key Science team PI's:
  - Gene Serabyn, JPL
  - Phil Hinz, Univ. of Arizona
  - Marc Kuchner, GSFC
- First shared-risk nuller science paper on observations of Nova RS Oph just accepted
  - R. K. Barry et al. "Milliarcsecond N-Band Observations of the Nova RS Ophiuchi,"2008, ApJ, accepted [arXiv:0801.4165]

Nuller Concept

- Two problems
  - Bright star
  - Bright background
- Approach: 4 beam interferometer
  - Split each Keck pupil into L and R halves
  - Null star on the two 85 m baselines (K1L+K2L; K1R+K2R) to improve the exozodi-to-star ratio
    (no SNR gain for ground-based obs.)
  - Combine and demodulate the nulled outputs on the short 4.1 m baseline
    - » Interferometric chopping to measure the nulled signal in a large background



Starlight Block Diagram



Interferometry basement

K1 in

K2 in

Long delay lines

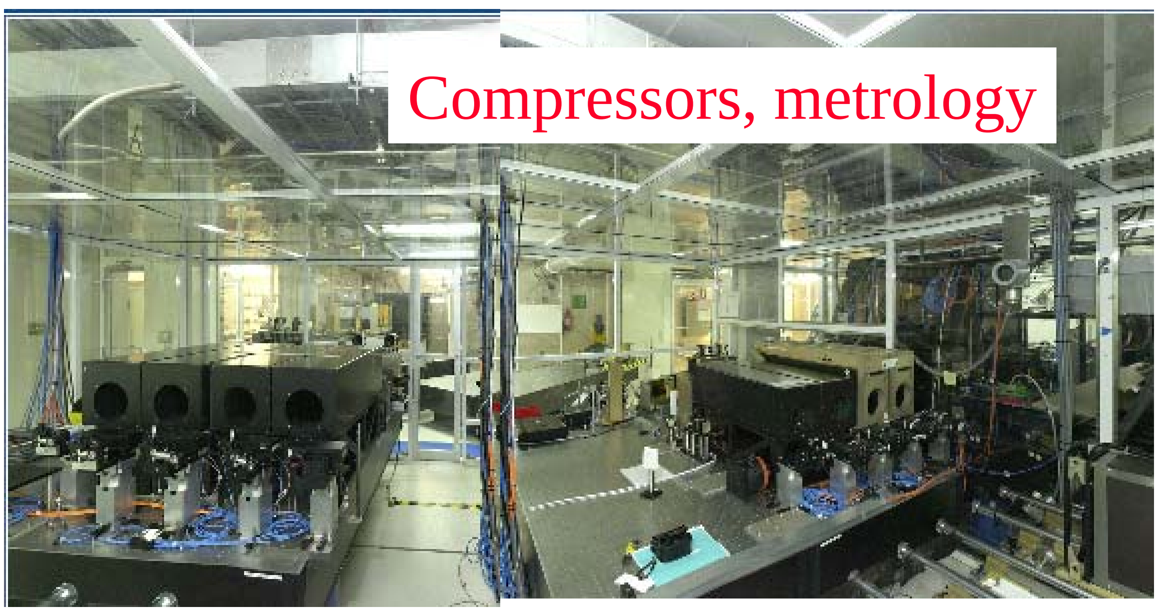
Beam combiners

Fast delay lines

Switchyard

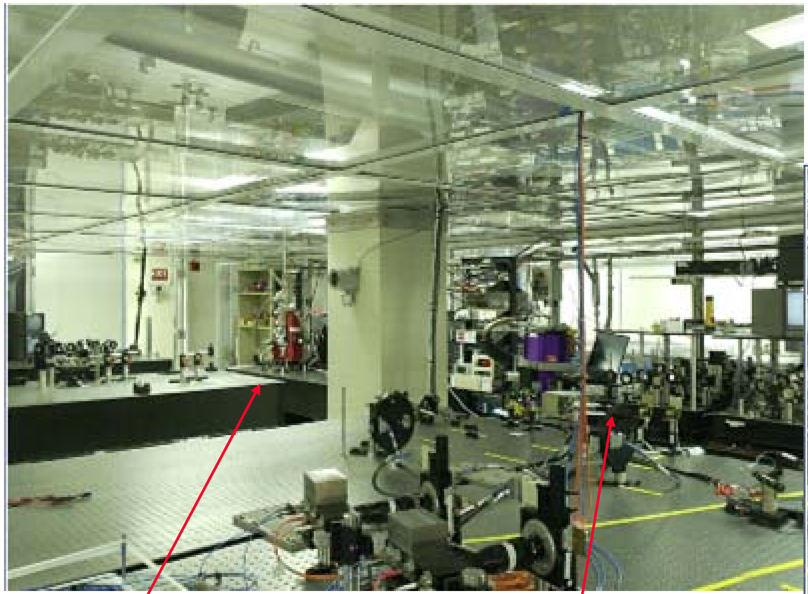
See virtual tour at planetquest.jpl.nasa.gov/Keck

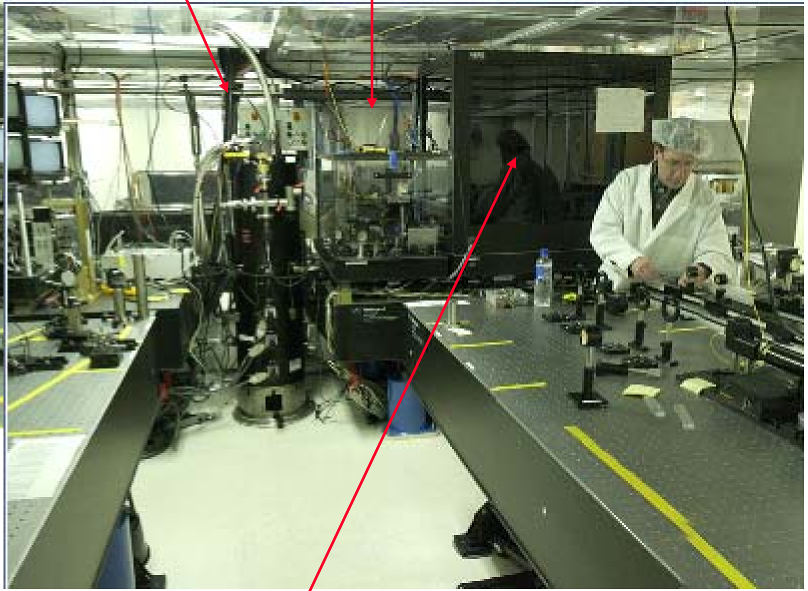
Fast delay line area



KALI

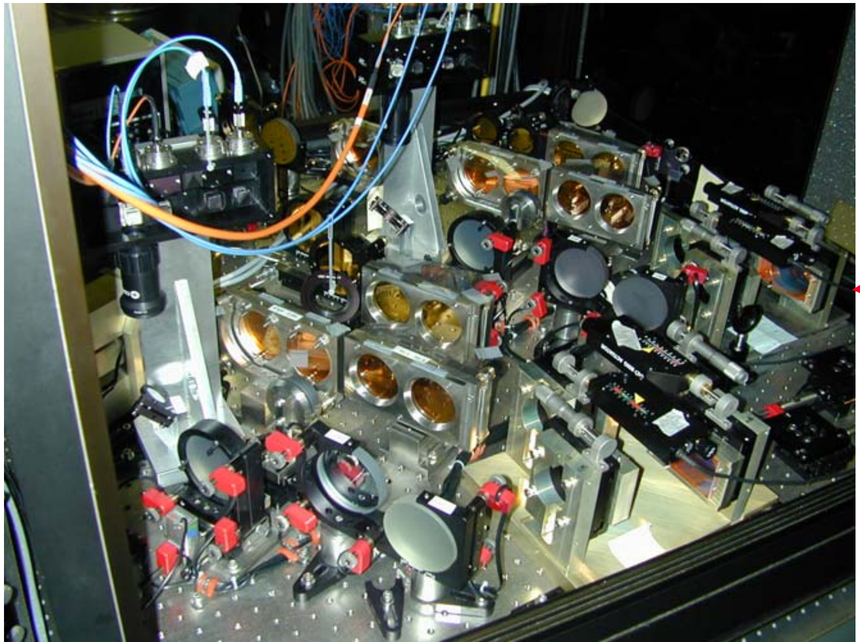
Nuller Stimulus





KAT

FATCAT



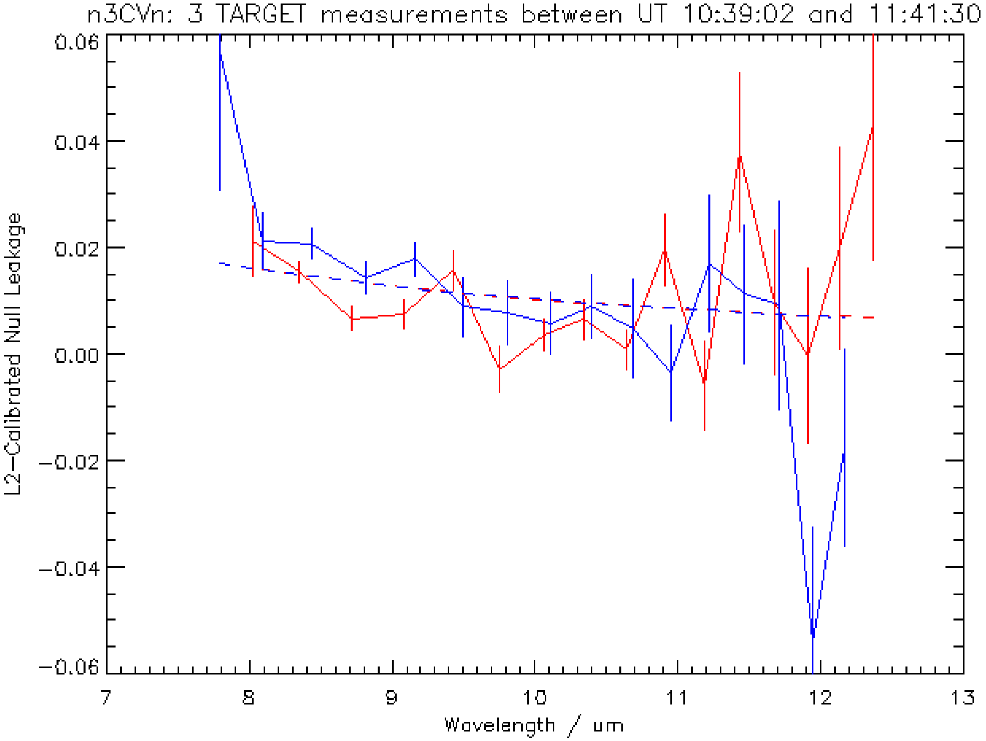
Nuller Breadboard

Beam combiner area

Observing scenario

Nulling

- Measure science target with interleaved calibrators
- From calibrators, compute "system leakage", i.e., 1 / Null Depth
- Calibrated Leakage is $L_{science} - L_{system}$
  - Accuracy of this quantity is key performance metric
- Analogous to V2 ops scenario



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Everything degrades the null

error budget terms for 1% leakage

1	**Differential OPD (windowed)**	$L = \frac{1}{4}\sigma^2_{\phi1-\phi2}$		300	(nm rms)
2	**Intensity balance**	$L = \frac{1}{4}[1-4I_1I_2/(I_1+I_2)^2\}$		50.0%	Δ, relative I difference btwn arms (%)
3	**Intensity fluctuations**	$L = 1/8\ \sigma^2_{Ii}$		28.0%	σ_{Ii}, total I rms each arm (%)
4	**Pure image rotation**	$L = \frac{1}{4}\theta^2$		12	θ, rotation (deg)
7a	**Static tilt with diff-limited det. Pinhole**	$L \cong 0.4\ (tp)^2$		0.160	t, total vector tilt *difference (waves)*
7b	**Dynamic tilt w/ diff-limited det. pinhole**	$L \cong 0.4\ (tp)^2$		0.160	t, total vector tilt difference (waves)
7e	**Ordinary shear with diff-limited det. pinhole**	$L \sim 0.4\ s'^2$		0.160	s', relative shear (frac of beam diameter)
8	**Focus + astigX,Y w/ diff-limited det. pinhole**	$L \cong 3\ w^2$		0.058	w, total rms phase difference in those modes (waves)
9	**Coma (4 terms) w/ diff-limited det. pinhole**	$L \cong 0.8\ w^2$		0.110	w, total rms phase difference in those modes (waves)
14b	**Amplitude curvature across pupil**	$L= (1/48)*(\Delta)^2$		0.700	Δ, peak I mismatch (%)
5	**Pure s-p phase shift**	$L = 1/16\ \phi^2$		23	ϕ (deg)

Dealing with the error budget

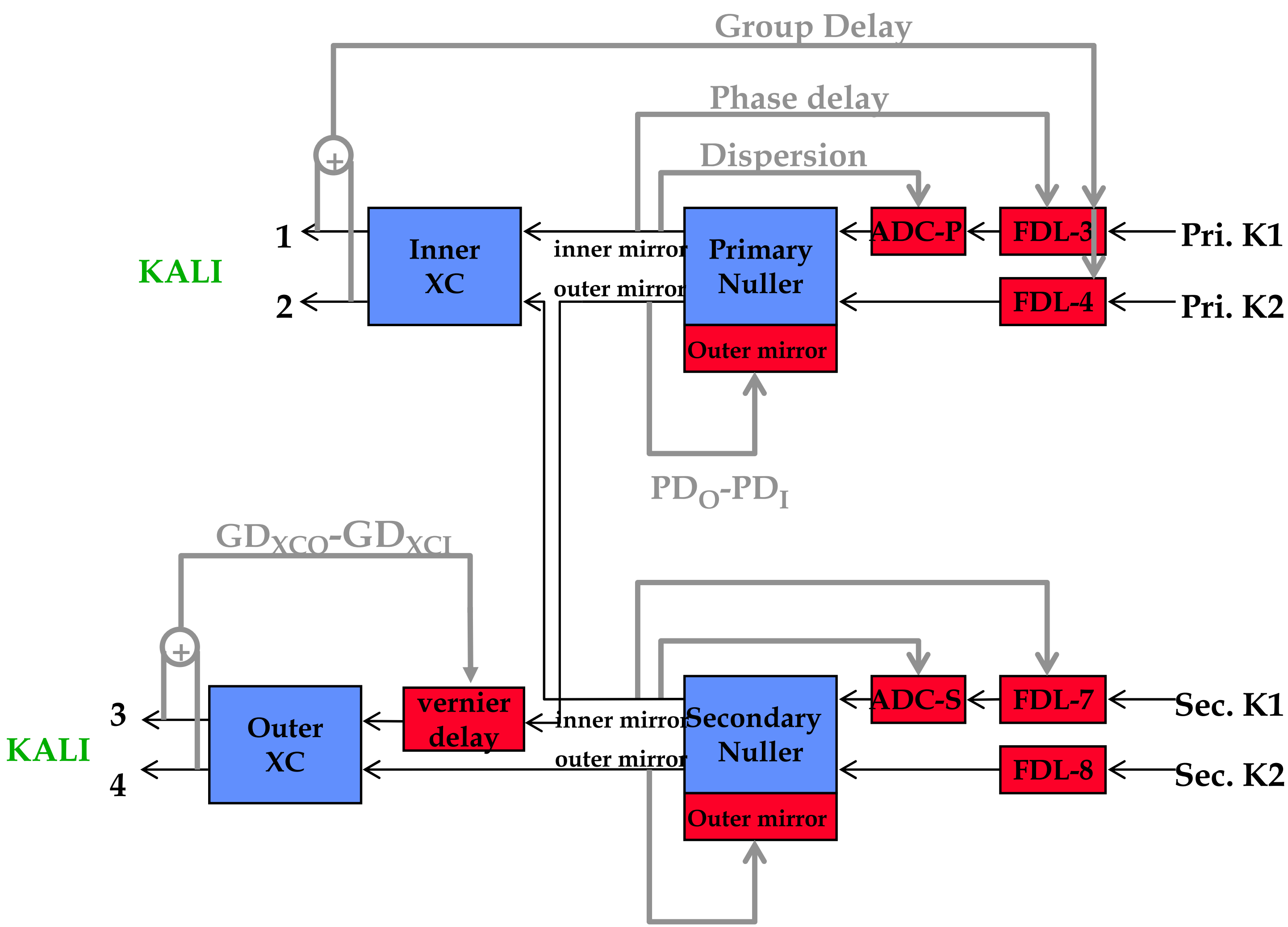
- Symmetry
  - Nuller beam combiner design
  - Beamtrain
    - » Coatings, rotation, etc.
- Spatial filtering
  - Camera has a 1.4 λ / D pinhole (+ other selections)
- Pointing and shear
  - Flux peak on bright star before each cluster
  - Automatic shear adjust for each star
- Cophasing
  - 300 nm rms needed for 1% leakage
  - Atmospheric moves 300 nm in 10 ms
  - 10 um sources don't have enough SNR in 10 ms for compensation
    - » Use 2 um system for fast tracking
      - Uses feedback control for the Fringe Tracker
      - Uses feedforward control to the Nuller
    - » Use 10 um system for slow tracking

Laser metrology and accelerometers

- External metrology
  - Measures common mode pathlengths from basement to telescope – 4 systems
- Internal metrology
  - Measures non-common mode pathlengths from fringe tracker and nuller to wavelength split – 4 differential systems
- Delay line metrology
  - Local delay line servo control – 8 systems
- Telescope accelerometers – 15 per telescope

- Implemented transparently to the fringe tracker and nuller

10 um starlight control loops



Multiplexing

- Laser metrology + 2 um fringe tracking + 10 um fringe tracking all simultaneous via WDM
  - Nuller is more problematic
    - » 1 wavelength, 1 camera: 3 fringe trackers
- A second issue – total flux calibration
  - V^2
    - » Measure fringe power N^2V^2
    - » Measure total flux N
    - » Compute normalized V^2
  - Nulling
    - » Measure coherent "null" power NL with both MMZs at Null
      - How to get N?
    - » Best approach for us is to measure coherent "peak" power with both MMZs at peak
- Leads to time-multiplexed sequence

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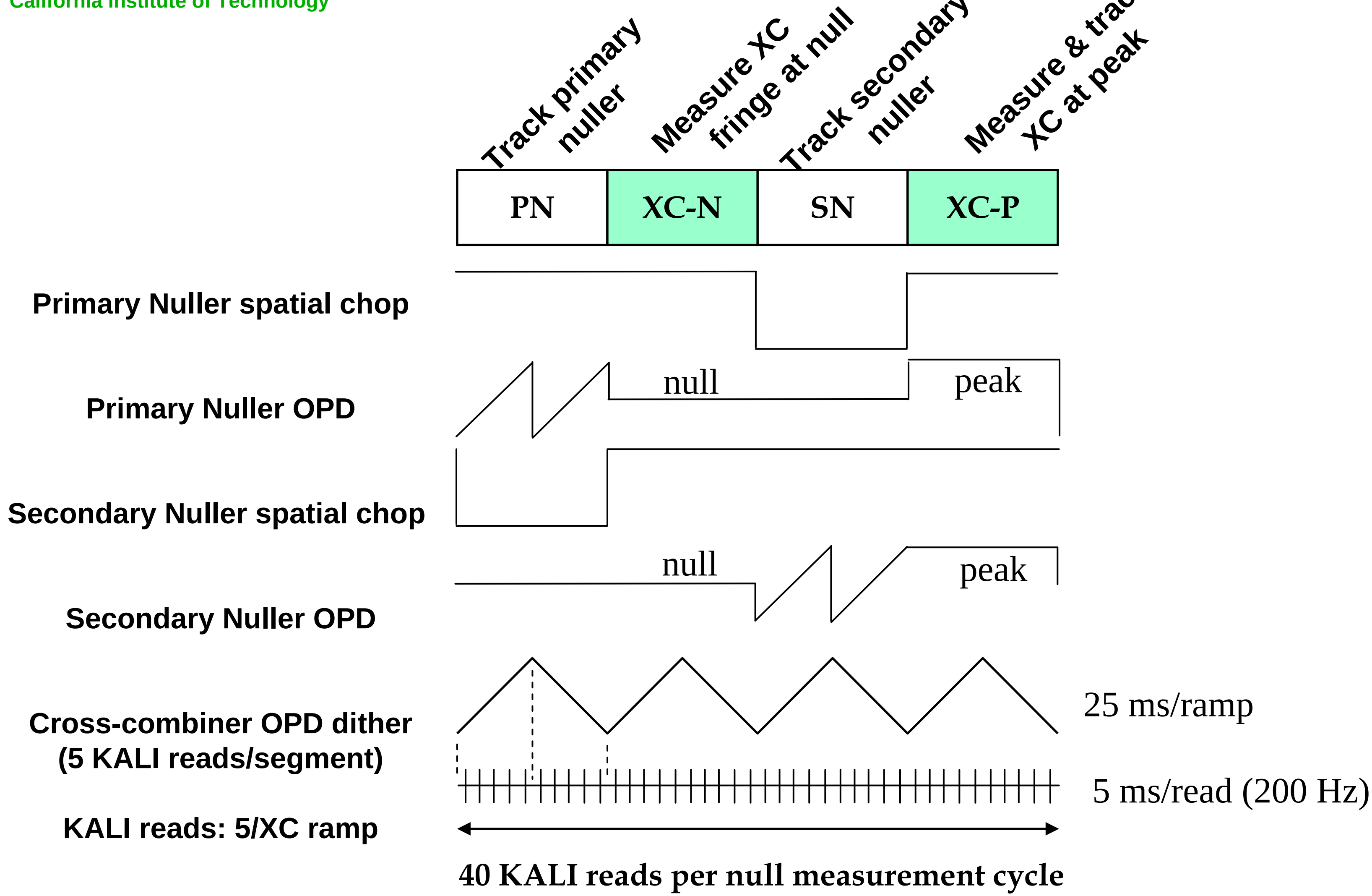
Null measurement sequence



This is the acquisition-mode sequence. The science-mode sequence spends more time at null, disables the spatial choppers, and servos the long baselines to directly minimize the null leakage